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PILOT-AIDED MODULATION FOR NARROW-BAND SATELLITE COMMUNICATIONS

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ABSTRACT

This paper discusses a number of tone-aided modulation techniques which have been studied as part of the Mobile Satellite Experiment (MSAT-X) Program. In all instances tone(s) are inserted into data-free portions of the transmit spectrum and used by the receiver to sense the amplitude and frequency/phase distortions introduced by the channel. The receiver then uses this information in a feedforward manner to lessen the effect of the distortions on the data detection performance. Particular techniques discussed are the Tone Calibration Technique (TCT), the Dual Tone Calibrated Technique (DTCT), Transparent Tone-In-Band (TTIB) and Dual-Tone Single Sideband (DTSSB).

INTRODUCTION

The goal of the Mobile Satellite Experiment (MSAT-X) is to develop concepts and technologies which enable the creation of a mobile satellite service. To accommodate a large number of users, it has been decided that each channel will be 5 kHz wide. In addition, these channels must support a data rate of 4800 bps in order to allow telephone quality digital voice communication using vocoders of reasonable complexity. A major challenge, then, is to develop a modulation format which can provide adequate detection performance for operation of the digital voice system while maintaining adequately low signal powers. It has been determined that bit error rates under 10^{-3} at a signal-to-noise ratio of 10 dB are needed for this system.

The mobile satellite system will involve communications from moving vehicles directly to and from the satellite. Consequently, the system must contend with the presence of reflected multipath signals as well as Doppler frequency shifts. Due to the narrow bandwidth of the signals and the desired operation at L-Band, these effects can become quite severe and some type of compensation must be applied in the receiver. Highly directional antennas will help reduce some of the multipath effects but some reflected components are expected in conjunction with the desired line-of-sight component. A modem for octa-Phase Shift Keying (8-PSK) using differential detection with a Doppler correction technique has been developed as part of the MSAT-X program. This system is discussed in (Simon, 1988).

An alternate method for mitigating the effects of multipath fading and Doppler frequency shifts is the use of tone aided modulation. A number of tone aided modulation formats have been investigated in conjunction with the MSAT-X program. The common feature of all these formats is that one or more tones are inserted into a portion of the transmit spectrum which does not contain any of the transmit data signal. These tones may reside at the edges of the data spectrum or in a frequency null that has been deliberately created within the data spectrum. In any case, the one or more tones are separated from the data signal at the receiver and used to determine the channel- and equipment-induced amplitude and phase/frequency distortions. It is assumed in this system that, due to the narrow channel bandwidth, these channel effects will be nearly uniform over the channel and, therefore, the distortion introduced in the tone(s) is the same as that introduced in the data signal.

The recovered pilot tone(s) contains the necessary information to reduce the effects of the channel distortions on the data signal. The envelope of the recovered pilot tone(s) provides information about the signal amplitude distortion. In addition, the frequency/phase modulation of the tone(s) provides an indication of the frequency and phase distortions. The basic structure of the receiver involves the recovery of amplitude and frequency/phase distortions from the pilot tone(s) and the subsequent feedforward processing of this information to compensate for the distortion effects in the data signal. Figure 1 shows the general receiver structure. The bandpass filter on the input performs the channel select function. As can be seen in the figure, the data signal is delayed in a path parallel to the pilot processor in order to maintain time alignment with the recovered distortion information obtained from the tone(s). This feedforward structure is superior to feedback techniques for this application because it allows the instantaneous "tracking" of fluctuations. In other words, the information used to correct the data signal at a particular time is obtained from the tone signal at that same time.

This paper discusses several tone-aided systems and provides information on the structure of the various receivers. Important considerations in the evaluation of the viability of a particular tone-aided format are the complexity of the modulator/demodulator structure, and the amount of extra bandwidth and power required for the insertion of the tone(s). The receiver structures presented are all bandpass (i.e. "IF") implementations, though baseband implementations are probably better suited to implementation using digital signal processors. The bandpass implementations are presented here because they more clearly illustrate the functions performed in each receiver type.

TONE CALIBRATED TECHNIQUE (TCT)

The TCT system (Davarian, 1984) employs Manchester encoding to create a null in the center of the data signal spectrum. A single pilot tone that is in phase coherence with the carrier is inserted into this null. Figure 2 shows the resulting transmit spectrum.

The TCT receiver, shown in Figure 3, consists of the pilot bandpass filter (PBPF) for the recovery of the pilot tone, the calibration system, a coherent demodulator and a Manchester decoder. The calibration system processes the pilot tone in two paths. The upper path squares the pilot tone and then lowpass filters the result to obtain the square of the pilot amplitude modulation. The lower path simply delays the pilot tone by an amount equal to the delay of the upper path. Finally, the delayed pilot tone is divided by the square of the amplitude modulation. The net result is that, if the pilot at the input to the calibration system has amplitude modulation A(t), the pilot at the output of the calibration system has amplitude modulation 1/A(t). The pilot processor output is fed to the data demodulator where it is used to coherently demodulate the data signal. Assuming that the data signal also has amplitude modulation A(t), the amplitude modulation terms vanish in the mixing process. Finally a Manchester decoder recovers the data.

The TCT system has been analyzed and implemented for binary PSK signalling. Although BPSK does not provide the required 4800 bps throughput in the 5 kHz channel, the results indicate that the major contribution of the pilot tone is the removal of the irreducible error floor associated with coherent receivers in the presence of Rician fading (Rafferty, 1987).

Despite this important performance advantage, the drawbacks of the TCT system reduce its value for mobile satellite applications. First, the use of Manchester coding to create a null for the pilot has the undesirable by-product of doubling the signalling rate and, therefore, the transmit bandwidth. As a consequence, the number of signalling states must be doubled to maintain the same throughput as a non-tone aided PSK system, causing a loss in detection efficiency. Second, the width of the spectral null proved to be too narrow for proper operation. A sufficiently wide null must be used because the pilot tone must be recovered using a filter which will pass the faded pilot tone when subjected to the Doppler frequency shifts. Using a pilot recovery filter with a minimum bandwidth necessary to accommodate the expected Doppler spread, it was found that unacceptable amounts of data signal energy passed through the filter and appeared in the recovered pilot tone. This signal energy resulted in pilot tone amplitude and phase modulation that was not channel-induced and, as a result, degraded system performance. Later studies used high pass filters in the transmitter to increase the width of the null, resulting in the introduction of inter-symbol interference (Rafferty, 1985).

DUAL TONE CALIBRATED TECHNIQUE (DTCT)

The problems encountered with the TCT system centered upon the creation of the spectral null for the pilot tone and the related bandwidth expansion. As a solution to this problem the DTCT system (Simon, 1986), which uses two pilot tones, was derived. This system places one tone on each side of the data signal as shown in Figure 4. The two tones are used in the receiver to create a coherent reference at the carrier frequency which, as in the TCT system, is used to demodulate the data.

Figure 5 is a block diagram of an implementation of the DTCT system. The input signal is bandlimited to set the channel bandwidth. The pilot tones are recovered using two pilot bandpass filters, one at frequency $\omega_0+\omega_p$ and a second at frequency $\omega_0-\omega_p$. The outputs from the pilot recovery filters are mixed together to produce a tone at frequency $2\omega_0$, i.e. twice the carrier frequency of the data signal. This signal is then fed to a calibration system similar to the TCT calibration system which outputs the $2\omega_0$ signal with amplitude modulation 1/A(t). A tone at frequency ω_0 is produced using a frequency divider and the result is used to coherently demodulate the data signal.

The main drawbacks of the DTCT system are the extra bandwidth required for two tones, the increased processing noise in the pilot recovery system due to the use of two pilots (each recovered pilot signal contains noise) and the placement of the tones at the band edge where they are more likely to be subject to distortions. Frequency uncertainty combined with non-ideal amplitude and phase characteristics of the receiver front end filters will create some phase distortion in the pilot tones which, in turn, will affect the efficiency of the coherent demodulation process.

TRANSPARENT TONE-IN-BAND (TTIB)

The TTIB system (McGeehan, 1984) in many ways combines the best attributes of the TCT and DTCT systems. Like the TCT system, the TTIB system utilizes a single pilot tone placed at the center of the transmit signal where the distortions due to filtering are expected to be minimal. However, the spectral null for the tone is created by the somewhat unusual approach of splitting the data spectrum in a single-sideband fashion and frequency shifting the upper half upwards by ω_T and the lower half downward by the same amount. The frequency shift value, ω_T, is set to accommodate the expected Doppler spread and allow for non-zero transition bands of the sideband separation filters. Figure 6 shows the TTIB spectrum. Like the DTCT system, the data bandwidth is not expanded by the insertion of the tone, however, the TTIB data signal appears as two sections.

Figure 7 is a block diagram of a TTIB receiver. The two main functions performed by the receiver are the pilot processing, which removes the amplitude and frequency/phase distortions, and the demodulator which which uses a phase-locked loop (PLL) to obtain an estimate of ω_T and, then, recombines the data sidebands.

The pilot processor splits the input signal into two paths, one path uses a notch filter to remove the pilot tone from the data sidebands and a second mixes the input signal with a subcarrier at ω_s and then uses a bandpass filter to isolate the pilot tone, now at frequency $\omega_s+\omega_T$. The pilot calibration system then inverts the amplitude modulation on the pilot. Finally, the data sidebands are mixed with the output of the pilot amplitude processor, resulting in the data sidebands on the subcarrier ω_s and some higher-order mixer products.

The output of the pilot processor is the data signal centered at frequency ω_s and containing the $2\omega_T$ spectral null. At this point, the amplitude and frequency uncertainty due to Doppler or fading has been removed through the pilot processing. The next portion of the receiver is a PLL which is a unique implementation of a Costas-type tracking loop which recombines the two sidebands by recovering the frequency shift term, ω_T. Note that the pilot processing effectively removes any significant frequency uncertainty at the input to the PLL. Consequently, a first order PLL is sufficient. Therefore the loop filter in Figure 7 is simply a gain block. The upper and lower sidebands of the pilot processor output are isolated by bandpass filters on the input to the PLL. These sidebands are then mixed to baseband using a locally generated references at $\omega_T+\omega_s$ and $\omega_T-\omega_s$, respectively. The error signal is generated by mixing these two baseband signals together. The error signal controls the voltage controlled oscillator (VCO) which generates the estimate of ω_T. Note that the PLL tracks ω_T

which is a stable frequency value and is not affected by the channel impairments.

The main disadvantages of the TTIB system are the complexity of the receiver and the non-ideal operation of the PLL which recovers ω_T. It has been found that, in processing the TTIB signal, this PLL contains a data dependent noise term in the error signal. This unwanted noise term is due to the single sideband nature of the signals and is proportional to the Hilbert Transform of the data signal (Saulnier, 1988). These data dependent terms, however, do not prevent the PLL from acquiring or maintaining lock, but may degrade its performance. Currently, experiments are being conducted to characterize the loop performance in AWGN and multipath fading. In particular the degradation in performance due to the undesired terms in the PLL error signal is being evaluated.

DUAL-TONE SINGLE SIDEBAND (DTSSB)

The DTSSB system transmits only one sideband of the data signal and uses two pilot tones, both on the same side of the data sideband, to provide frequency and amplitude compensation as well as a coherent reference for demodulation. Like the DTCT and TTIB systems, this approach does not expand the bandwidth of the data signal. Unlike the TTIB system, the DTSSB system does not require a PLL for data recovery and therefore, will not introduce the data dependent noise. However, the use of two pilots does introduce additional noise in the pilot processing and, consequently, it is not clear whether the DTSSB system provides a performance advantage over the TTIB system.

Figure 8 shows the DTSSB spectrum. One pilot tone is placed a frequency ω_T from the carrier of the single sideband. The second tone is placed ω_T from the other tone, i.e. $2\omega_T$ from the carrier. The receiver recovers both tones and uses the difference frequency to determine ω_T and, then, uses ω_T to regenerate a coherent carrier reference. The net result is that the single sideband is coherently demodulated.

Figure 9 is a block diagram of the DTSSB receiver. Two bandpass filters, one centered at frequency ω_0 and the other at $\omega_0+\omega_T$, are used to isolate the two pilots. One pilot is processed by a calibration system to replace its envelope with its inverse, i.e. A(t) is replaced by 1/A(t). The amplitude-processed pilot is then mixed with the other recovered pilot to produce a frequency term at frequency ω_0. This ω_0 term is then mixed with the calibration system output to produce a tone at the data sideband carrier frequency, $\omega_0-\omega_T$. Finally, coherent demodulation is performed to recover the data.

The main concerns with the DTSSB system are the asymmetry of the transmit signal and the distortion of the phase relationship between the pilots by the receiver front end filtering. Any error in this phase relationship will degrade the coherent demodulation process. Also, the use of two pilots introduces additional noise into the demodulation process as in the DTCT system. An advantage of the DTSSB system is the efficient use of the bandwidth by the transmission of only a single data sideband.

DISCUSSION AND CONCLUSIONS

This paper presents four pilot-aided modulation schemes and discusses some of the properties of each. The TCT system uses a very simple receiver but suffers from the excessive bandwidth expansion caused by the use of Manchester encoding. The DTCT system uses two pilots and is more bandwidth efficient than the TCT system. The placement of the tones at the edges of the channel make this technique susceptible to degradation from non-ideal receiver filtering and, in particular, non-uniform group delay distortion. The TTIB system is more bandwidth efficient than the DTCT system because it requires only one pilot tone. The TTIB receiver,however, is much more complex than those for the other techniques due to the need for the PLL. Currently, it has not been determined if the presence of data dependent terms in the PLL error signal will seriously degrade performance. Finally, the DTSSB system provides excellent bandwidth efficiency and uses a simple receiver structure. However, the asymmetry of the signal spectrum and the additional noise due to the use of two pilots may degrade the performance of this system.

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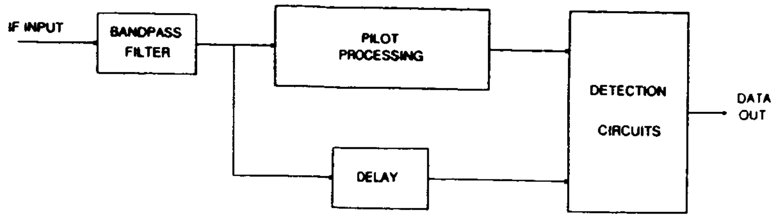

Fig. 1 General tone-aided receiver

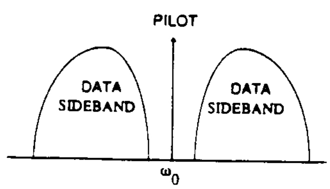

Fig. 2 TCT spectrum

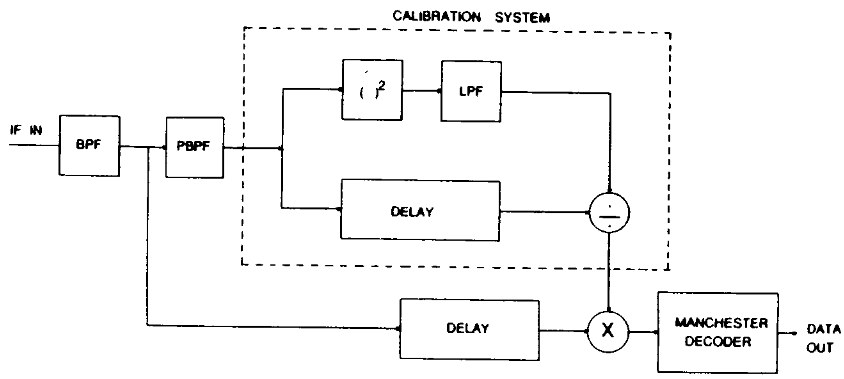

Fig. 3 TCT receiver structure

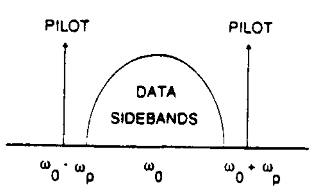

Fig. 4 DTCT spectrum

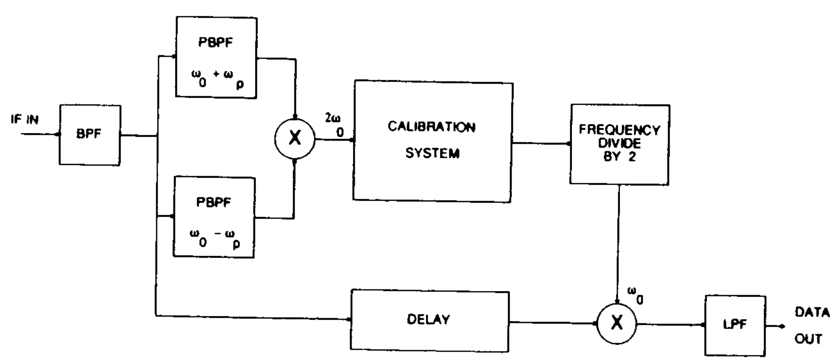

Fig. 5 DTCT receiver structure

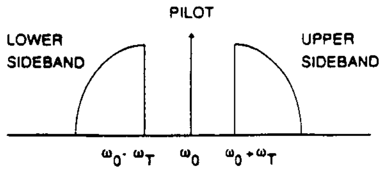

Fig. 6 TTIB spectrum

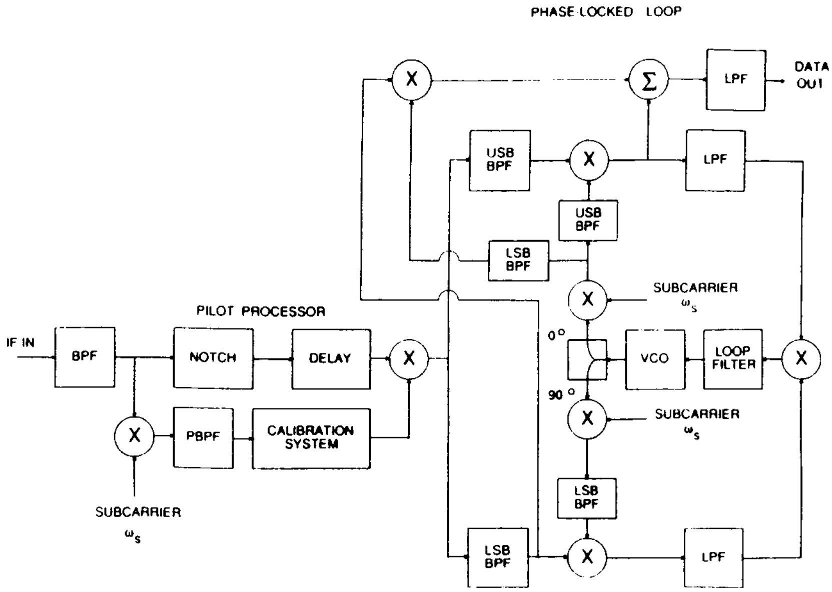

Fig. 7 TTIB receiver structure

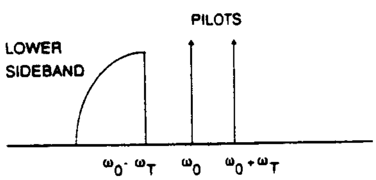

Fig. 8 DTSSB spectrum

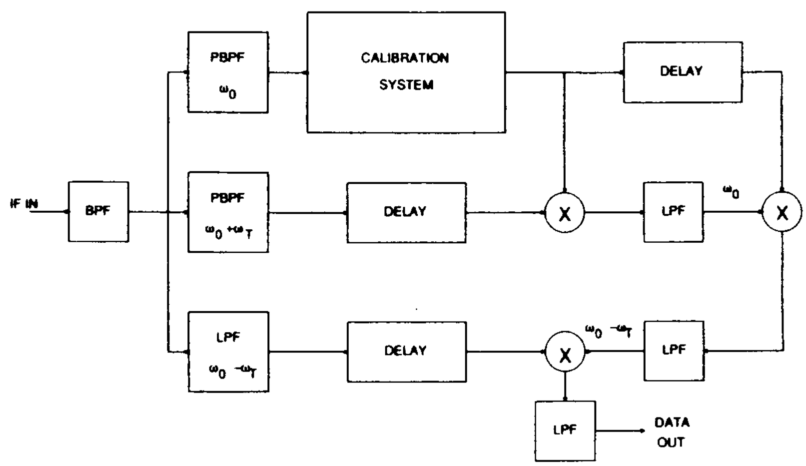

Fig. 9 DTSSB receiver structure